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ORIGINAL ARTICLE

Validating measures of free-living physical activity in overweight and obese subjects using an accelerometer

G Valenti[1], SGJA Camps[1], SPM Verhoef[1], AG Bonomi[2] and KR Westerterp[1]

BACKGROUND: Free-living physical activity can be assessed with an accelerometer to estimate energy expenditure but its validity in overweight and obese subjects remains unknown.
OBJECTIVE: Here, we validated published prediction equations derived in a lean population with the Tracmor_D accelerometer (DirectLife, Philips Consumer Lifestyle) in a population of overweight and obese. We also explored possible improvements of new equations specifically developed in overweight and obese subjects.
DESIGN: Subjects were 11 men and 25 women (age: 41 ± 7 years; body mass index: $31.0 \pm 2.5\,\text{kg}\,\text{m}^{-2}$). Physical activity was monitored under free-living conditions with Tracmor_D, whereas total energy expenditure was measured simultaneously with doubly-labeled water. Physical activity level (PAL) and activity energy expenditure (AEE) were calculated from total energy expenditure and sleeping metabolic rate.
RESULTS: The published prediction equation explained 47% of the variance of the measured PAL ($P < 0.001$). PAL estimates were unbiased (errors (bias $\pm$ 95% confidence interval): -0.02 ± 0.28). Measured and predicted AEE/body weight were highly correlated ($r^2 = 58\%$, $P < 0.001$); however, the prediction model showed a significant bias of $8\,\text{kJ}\,\text{kg}^{-1}$ per day or 17.4% of the average AEE/body weight. The new prediction equation of AEE/body weight developed in the obese group showed no bias.
CONCLUSIONS: In conclusion, equations derived with the Tracmor_D allow valid assessment of PAL and AEE/body weight in overweight and obese subjects. There is evidence that estimates of AEE/body weight could be affected by gender. Equations specifically developed in overweight and obese can improve the accuracy of predictions of AEE/body weight.

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INTRODUCTION

Physical inactivity results in reduced activity energy expenditure (AEE), which contributes to positive energy balance. A prolonged positive energy balance leads to weight gain and therefore to overweight and obesity. Guidelines suggest that weight loss and maintenance should combine dietary therapy with an AEE of at least 5–8 MJ per week.[1] These guidelines report that the promotion of physical activity and increased AEE is an important aspect of intervention strategies for weight maintenance after weight loss. Accurate assessments of AEE are therefore necessary to describe and promote long-term interventions. Techniques for estimating AEE should imply minimal discomfort for the subjects and must be validated under free-living conditions.

The gold standard for measurements of free-living total energy expenditure (TEE) is the doubly-labeled water (DLW) method.[2] Physical activity level (PAL) and AEE can be derived from TEE combined with basal metabolic rate, that is, the energy requirement of vital functions. When PAL and AEE are derived from DLW, no insight into physical activity patterns can be provided. Furthermore, studies based on DLW usually include relatively small populations. Accelerometers, instead, can provide physical activity patterns in large populations when they can accurately estimate AEE and PAL under free-living conditions.[3]

Over 20 prediction equations developed with accelerometers have been validated to assess energy expenditure under free-living conditions.[4] These validation studies are conducted mostly in healthy lean adults. The results reported cannot be extended to overweight populations before their generalizability is verified with a specific validation. Only two of the equations validated in lean subjects have been tested in overweight and obese. In 1998, Fogelholm *et al.*[5] estimated DLW measurements of TEE from the Caltrac accelerometer with unpublished built-in algorithms in 20 overweight women. They reported a weak correlation ($r^2 = 0.11$, $P = 0.15$) between measured and predicted TEE owing to the fact that an accelerometer cannot assess basal metabolic rate, which constitutes about 60% of TEE.[6] We consider that an estimation of AEE from accelerometer data would have been more appropriate. Furthermore, the Caltrac was worn only on days 1, 3, 6, 8 and 12 of the DLW measurement period of 14 days. This systematic selection of the measurement days could have affected the results. More recently, Jacobi *et al.*[7] validated the TR3 accelerometer in 13 overweight subjects to estimate AEE simultaneously with DLW measurements. The study reported a significant correlation ($r^2 = 0.45$, $P < 0.05$) between measurements and estimates of AEE. However, AEE was not adjusted for individual differences in body size, which could explain why it was concluded that the TR3 could provide accurate estimations only at a group level. Furthermore, the small group size and the limited variance of AEE (2.9 ± 0.9 MJ per day) could have reduced the predictive value of the accelerometer. Other accelerometers like the DynaPort (DynaPort MiniMod; McRoberts B.V., The Hague, The Netherlands) were used

[1]Department of Human Biology, Maastricht University, Maastricht, The Netherlands and [2]Personal Health Solutions, Philips Research Laboratories, Eindhoven, The Netherlands. Correspondence: G Valenti, Department of Human Biology, Maastricht University, PO Box 616, Maastricht 6200 MD, The Netherlands.
E-mail: g.valenti@maastrichtuniversity.nl
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in studies involving obese subjects without validation in overweight and obese under free-living conditions against DLW.[8]

The aim of this study was to validate published prediction equations derived in a lean population[9] with the $Tracmor_D$ accelerometer (DirectLife, Philips Consumer Lifestyle, Amsterdam, The Netherlands) to estimate free-living AEE and PAL in overweight and obese subjects with DLW as the reference. We also explored possible improvements of new equations specifically developed in overweight and obese subjects.

SUBJECTS AND METHODS

Subjects

Subjects were 11 men and 25 women, aged 41 ± 7 years and body mass index (BMI) 31.0 ± 2.5 kg m^{-2} (Table 1). All subjects were included in the final analysis. Written informed consent was obtained and the Ethics Committee of the Maastricht University Medical Center approved the study. The study was registered in ClinicalTrials.gov (registration number: NCT01015508).

Study design

The study included a 2-week measurement period of physical activity with $Tracmor_D$. TEE was measured simultaneously with DLW. At the beginning of the study, subjects spent one night in a respiration chamber. The morning after, and before breakfast, anthropometric measurements were taken. Body mass was measured on an electronic scale (Life Measurement Corporation Inc., Concord, CA, USA) to the nearest 0.01 kg. Height was measured to the nearest 0.1 cm.

Energy expenditure

Sleeping metabolic rate (SMR) was measured during an overnight stay in a respiration chamber. The chamber is an airtight room that measures 14 m^3 and is furnished with bed, table, chair, freeze toilet, washing bowl, radio, television and a computer.[10] Subjects entered the chamber at 2100 hours in the evening and left the chamber at 0730 hours the following morning. Subjects were not allowed to eat during their stay in the chamber. Energy expenditure was calculated from O_2 consumption and CO_2 production according to Brouwer's formula.[11] SMR was defined as the lowest observed energy expenditure for three consecutive hours during the night. Room temperature was held constant at 20 ± 1 °C.

TEE was measured using DLW according to the Maastricht protocol.[12] Briefly, after the collection of a baseline urine sample on the evening of day 0, subjects drank a weighted amount of $^2H_2^{18}O$. The result is an initial increase in the body water enrichment of about 120 p.p.m. for ^2H and about 240 p.p.m. for ^{18}O. Urine samples were than collected in the mornings (from the second voiding) of days 1, 8 and 15, and in the evening of days 1, 7 and 14. PAL and activity-related energy expenditure (AEE) were then derived from TEE measured with DLW. PAL was calculated as TEE divided by SMR. AEE was calculated as (0.9 × TEE) − SMR, assuming the diet-induced thermogenesis to be 10% of TEE[13] and was then adjusted for body mass (AEE_{kg} = AEE/BM).

Table 1. Subject characteristics (values are mean ± s.d.)

Gender (M/F)	11/25
Age (years)	41 ± 7
Height (m)	1.71 ± 0.09
Body mass (kg)	90.3 ± 10.7
BMI (kg m^{-2})	31.0 ± 2.45
$Tracmor_D$ (MCounts per day)	1.54 ± 0.41
Wearing days (days)	11 ± 3
Wearing time (h per day)	16 ± 1
TEE (MJ per day)	12.3 ± 2.0
SMR (MJ per day)	6.9 ± 0.9
AEE (MJ per day)	4.1 ± 1.2
AEE_{kg} (kJ kg^{-1} per day)	46 ± 13
PAL	1.77 ± 0.19

Abbreviations: AEE, activity-related energy expenditure; AEE_{kg}, AEE divided by body mass; BMI, body mass index; SMR, basal metabolic rate; PAL, physical activity level (TEE/SMR); SMR, sleeping metabolic rate; TEE, total energy expenditure; $Tracmor_D$, $Tracmor_D$ output.

Accelerometry

Free-living activity was monitored from days 1 to 14 with $Tracmor_D$ (DirectLife, Philips Consumer Lifestyle) positioned on the lower back using a belt, as described before.[9] Subjects reported in a diary periods in which the $Tracmor_D$ was not worn. At the end of the measurement, data were downloaded from the $Tracmor_D$ using dedicated software (DirectLife, Philips Consumer Lifestyle). The output was expressed in activity counts per minute. Counts per day were calculated integrating counts per minute over each day. Average counts per day were calculated over the days of measurement. Days during which data were missing or subjects carried the accelerometer for < 10 h were excluded and the average was calculated on the remaining data, considering daily physical activity an ergodic process. Subjects with at least two valid days were included. Following these criteria, no subject was excluded.

Data analysis

Two simple linear equations developed by Bonomi *et al.*,[9] based on average daily counts, were applied to our population to cross-validate the estimations of PAL and AEE_{kg} (activity-related energy expenditure divided by body mass). The criteria were the measurements of PAL and AEE_{kg} based on indirect calorimetry methods, as described before. In addition, we explored possible improvements of developing specific equations in our population. The new equations were calculated with two simple linear regressions, with counts as independent variable and the criteria as dependent variables. All overweight and obese subjects were included in the training of the equations. Estimation errors of all equations were calculated as difference between estimations and criteria. Standard error of the estimate (SEE) was calculated as the root mean square of the errors. Pearson's sample correlation coefficient was used to test agreement between estimations and measurements, as well as between errors and BMI. Squared correlation coefficient between dependent and independent variables was calculated as coefficient of determination (simple linear regression). The level for statistical significance was set at $P < 0.05$.

RESULTS

Subjects were overweight and obese adults with a predominance of female subjects (Table 1). The $Tracmor_D$ was worn 13 ± 1 days during 15 ± 2 h per day indicating a high compliance. On average 12 ± 3 days were valid. Gender or other subject characteristics did not influence the compliance.

Validation of published equations

The prediction equation of PAL significantly explained the variance of the measured values ($r = 0.69$, $P < 0.001$). The estimates were unbiased with an average error of −0.02 ± 0.14 that corresponded to −1.1 ± 8.0% of the average PAL. This resulted in an SEE of 0.14 or 8.0% of the average PAL (Table 2). Errors were correlated with measured PAL ($r = -0.84$, $P < 0.001$) but not with BMI ($r^2 = 0.01$, $P > 0.5$).

Measured and predicted AEE_{kg} were highly correlated ($r = 0.76$, $P < 0.001$); however, the prediction model showed a significant bias of 8 ± 8 kJ kg^{-1} per day or 17.4 ± 17.4% of the average AEE_{kg} ($P < 0.0001$). This resulted in an SEE of 11 kJ kg^{-1} per day (24.9% of the average AEE_{kg}). Estimation errors correlated with measures ($r = -0.57$, $P < 0.001$) but not with BMI ($r^2 = 0.01$, $P > 0.5$).

Development of new prediction equation

The explained variance of the new prediction equation of PAL ($r = 0.69$, $P < 0.001$) was the same as the earlier equation applied to overweight and obese subjects. The variance and the SEE did not reduce with respect to the published equations (SEE = 0.14 or 8.0% of the average PAL). Errors were correlated with measured PAL ($r = -0.73$, $P < 0.001$) but not with BMI ($r^2 = 0.01$, $P > 0.5$) (Figure 1).

As in the published prediction equation applied to overweight and obese subjects, measured AEE_{kg} and predictions from the new equation were highly correlated ($r = 0.76$, $P < 0.001$). In the new equation, the variance of the error did not reduce with respect to the published equation (8 kJ kg^{-1} per day or 17.4% of the average AEE_{kg}), reducing the SEE to 8 kJ kg^{-1} per day. Estimation errors correlated with AEE_{kg} measures ($r = -0.65$, $P < 0.001$) but not with BMI ($r^2 = 0.01$, $P > 0.5$).

Table 2. Explained variation and errors statistics of the prediction equations previously validated in lean subjects[9] applied to a population of overweight and obese ($N = 36$), in comparison with the newly developed equation

Parameter	AEE_{kg} (kJ kg^{-1} per day)		PAL	
	Published equation	New equation	Published equation	New equation
r	0.76*	0.76*	0.69*	0.69*
SEE				
Value	11	8	0.14	0.14
Rel (%)	24.9	17.4	8.0	8.0
ME				
Value	8	—	−0.02	—
Rel (%)	17.4	—	−1.1	—
Linear trend	−0.57*	−0.65*	−0.84*	−0.73*

Abbreviations: AEE_{kg}, activity-related energy expenditure divided by body mass; ME, mean error; PAL, physical activity level (total energy expenditure/sleeping metabolic rate); *r*, correlation between estimated and measured values; Rel, relative value as a percentage of the mean measure; SEE, standard error of the estimate. Linear trend, linear correlation between errors and reference values as a measure of systematic linear bias. *$P < 0.001$.

DISCUSSION

The aim of this study was to validate published $Tracmor_D$ equations to estimate free-living AEE in overweight and obese subjects with DLW as the reference. We also explored possible improvements of new equations specifically developed in overweight and obese subjects. Forty-seven percent of the variance of PAL and 58% of the variance of AEE_{kg} were explained by the prediction equations, which were the highest explained variances reported so far in free-living overweight and obese subjects. Equations specifically developed for overweight and obese subjects did not lead to significant improvements in the estimates and errors.

The explained variation of PAL was statistically significant and comparable between the population of overweight and obese subjects and the population of lean subjects (47%, $P < 0.001$ vs 46% $P < 0.001$). The estimates of PAL in our population were unbiased and the variance of the error was comparable to the one reported by Bonomi *et al.*[9] in lean subjects, which resulted in a similar SEE (0.14 vs 0.13). Furthermore, the PAL prediction equation specifically developed for overweight and obese subjects did not lead to a relevant improvement in the estimates errors. Thus, our study extends the validity of the published equation to estimate PAL from the $Tracmor_D$ to a population of overweight and obese.

In 2011, Assah *et al.*[14] reported that an Actiheart could explain only from accelerations 29% ($P = 0.001$) of the variance of AEE_{kg} in African adults with an SEE of 38 kJ kg^{-1} per day and a significant bias of 27 kJ kg^{-1} per day. The authors concluded that the Actiheart could estimate AEE_{kg}. In the current study, estimates of AEE_{kg} explained a higher percentage of the variance of AEE_{kg} (58%, $P < 0.001$) with a lower SEE (11 kJ kg^{-1} per day) and a lower bias (8 kJ kg^{-1} per day). When compared with the study of Bonomi *et al.*,[9] the explained variance found in our population was slightly higher (58% vs 50%). This resulted in a lower variance of the error, which compensated for the bias, and resulted in an SEE

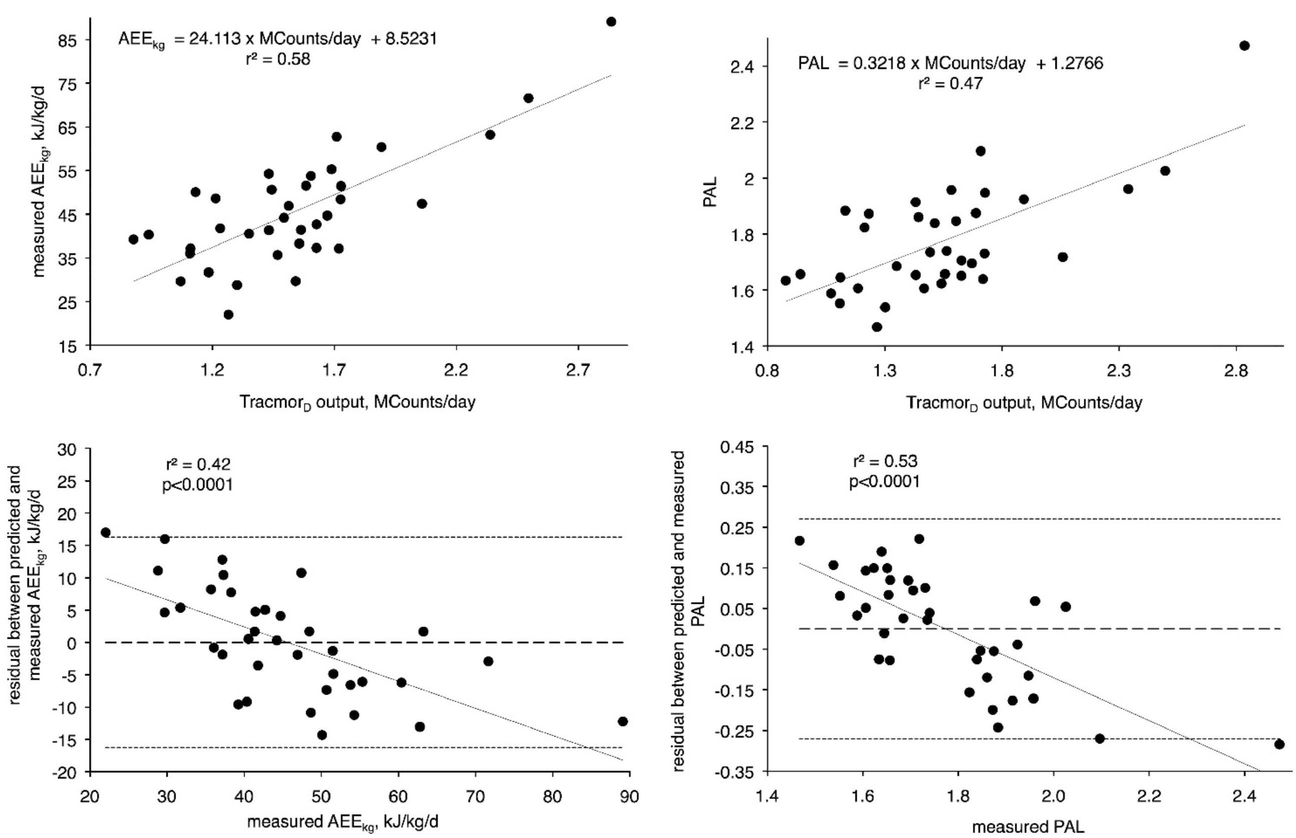

Figure 1. Regressions, equations and residual plots (mean error and confidence interval) of the prediction equations of activity-related energy expenditure divided by body mass (AEE_{kg}) and PAL developed in overweight and obese subjects.

lower than the one reported by Bonomi (11 vs 12 kJ kg^{-1} per day). Another consequence of an increased explained variance was that the new estimation equation for AEE_{kg} from activity counts had a reduced variance of the errors. Because the variance of the errors was lower, SEE was also reduced (11 vs 8 kJ kg^{-1} per day). This reduction, although significant, was practically irrelevant as we consider 11 kJ kg^{-1} per day a reasonable SEE and the reduction to 8 kJ kg^{-1} per day would require further studies to be extended to other populations. Thus, the development of a specific equation is not necessary to improve the estimations in our population. The validity of the AEE_{kg} prediction equation derived with $Tracmor_D$ in lean subjects is therefore extended to overweight and obese.

The bias found for the AEE_{kg} estimates was proportionally larger than the one for PAL estimates (17% vs −1%). This fact can be explained by comparing SMR and subject characteristics between the overweight and obese population and the lean used to develop the prediction equations (Table 1). An increased SMR would be expected from subjects with a higher body mass and therefore a higher fat free mass. Nevertheless, the gender distribution in the two populations was not equal: there was a predominance of male subjects in the lean population and a predominance of female subjects in the overweight and obese group. Female subjects are known to have a lower percentage of fat free mass, which compensated in the overweight and obese population for the increase in weight.[15] The result of this was an overcorrection of AEE in overweight and obese subjects, leading to artificially low measured values and therefore a positive bias and an increased SEE. This result did not affect the calculation of PAL as it is derived only from TEE and SMR and it does not require adjustment for body size. There is therefore evidence that estimates of AEE_{kg} could be affected by gender when comparing subjects with a wide range of BMI. For this reason, in the quantification of physical activity, PAL should be preferred to AEE_{kg} or gender should be included in a more complex model.

A negative linear trend was found between errors of AEE_{kg} and PAL when compared with the measured values. This means that subjects with a low level of physical activity were overestimated and *vice versa*, resulting in a bigger variance of the error. However, the SEE of AEE_{kg} and PAL were consistent with those reported in lean subjects and we can assume that this linear trend would not restrict the applicability of the method in free-living subjects.

A limitation of this study is the assumption that activity counts and energy expenditure are linearly related. This assumption is generally accepted and it implies the possibility to estimate AEE_{kg} or PAL from daily activity counts using a linear equation. Nevertheless, it has been shown that an *a priori* classification of the type of activity can improve the assessments of energy expenditure.[16] Simpler classification models have been developed to deal with the nonlinearity between accelerometer output and energy expenditure. Crouter *et al.*[17,18] classified the activities into two categories . They developed from this classification a two-regression model that was shown to be more accurate than a simple linear model for estimating METs. However, this more computationally sophisticated technique has not yet been shown to be valid in obese subjects as it was validated under free-living conditions in a population of mostly non-obese subjects (BMI 25.0 ± 4.6, range 19.3–37.4 kg m^{-2}). Applying a similar method to the $Tracmor_D$ might improve the estimation error described in this study both in lean and in overweight and obese populations.

In conclusion, our study showed that two published equations derived with $Tracmor_D$ allow valid assessment of physical activity in overweight and obese subjects with low errors. In particular, the explained variance of the dependent variables was the highest reported so far in free-living overweight and obese subjects. Validity of PAL and AEE_{kg} prediction equations developed in lean subjects is therefore extended to subjects with high BMI. There is evidence that estimates of AEE_{kg} could be affected by gender when comparing subjects with a wide range of BMI. $Tracmor_D$ can be reliably used to monitor increasing levels of physical activity in overweight and obese subjects.

CONFLICT OF INTEREST

AGB is employed at Philips Research Laboratories. The remaining authors declare no conflict of interest.

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AUTHOR CONTRIBUTIONS

KRW and SPMV designed the study. SGJAC and SPMV collected the data. GV analyzed the data and wrote the manuscript. KRW and AGB contributed to the interpretation of the data and reviewed the manuscript. The study was executed under supervision of KRW. All authors read and approved the final manuscript.

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